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# Research Strategy for Modeling the Complexities of Turbine Heat Transfer

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# RESEARCH STRATEGY FOR MODELING THE COMPLEXITIES OF TURBINE HEAT TRANSFER

by

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## INTRODUCTION

There is no shortage of complex heat transfer problems, so the title problem is merely one with which the author is familiar and one for which we have a nice story to tell. Being more specific, the subject of this paper is a NASA research program, known as the Coolant Flow Management Program, which focuses on the interaction between the internal coolant channel and the external film cooling of a turbine blade and/or vane in an aircraft gas turbine engine. As can be seen in a frequently used illustration, figure 1, the turbine gas path is really a very complex flow field. The combination of strong pressure gradients, abrupt geometry changes and intersecting surfaces, viscous forces, rotation, and unsteady blade/vane interactions all combine to offer a formidable challenge. To this, in the high pressure turbine, we add the necessity of film cooling.

The ultimate goal of the turbine designer is to maintain or increase the high level of turbine performance and at the same time reduce the amount of coolant flow needed to achieve this end. Simply stated, coolant flow is a penalty on the cycle and reduces engine thermal efficiency. Accordingly, understanding the flow field and heat transfer associated with the coolant flow is a priority goal. It is important to understand both the film cooling and the internal coolant flow, particularly their interaction. Thus, the motivation for the Coolant Flow Management Program.

The paper will begin with a brief discussion of the management and research strategy, will then proceed to discuss the current attack from the internal coolant side, and will conclude by looking at the film cooling effort - at all times keeping sight of the primary goal the interaction between the two. It should be emphasized that this paper is a discussion of an approach to a problem and not a comprehensive review of the subject. Only references specifically related to the program are listed and cited. Also, since this is fairly early in a work in progress, many of the references are either private communication or papers being submitted to conferences. The reader is referred to Simoneau and Simon (1993) and Iacovides and Launder (1995) for more general discussions and references on external and internal turbine blade cooling.

One of the themes of this paper is that complex heat transfer problems of this nature cannot be attacked by single researchers or even groups of researchers, each working alone. It truly needs the combined efforts of a well-coordinated team to make an impact. Despite the fact that there is only one author, it is important to note that this is a team effort. The government players on the team are specifically acknowledged at the end of this introduction and the industry and university contributions are clearly identified throughout the paper.

The author wishes to acknowledge the NASA personnel, including both the civil service staff and support service contractors, who are the government arm of this effort and who have provided most of the material presented herein. They include: Herbert J. Gladden, Steven A. Hippensteele, Philip E. Poinatte, Douglas R. Thurman, James A. Heidmann, Kestutis C. Civinskas, and John

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R. Schwab of NASA; David E. Rigby and Hien Lai of NYMA Inc.; Vijay K. Garg and Ali Ameri of AYT Inc.; and Erlendur Steinthorsson of ICOMP. The contributions from our industry and university partners will be noted, as they appear.

## RESEARCH STRATEGY

The first cornerstone of the research strategy is that complex problems of this nature cannot be solved by a single approach. Nor can they be solved by multiple, but disconnected, approaches. A dataset, a computer program, a turbulence model - none by themselves can solve the problem; however, taken together in an interactive manner they can be powerfully synergistic. Thus, the research model for this and most major research programs at NASA Lewis is the interactive computational/experimental/modeling model, illustrated in figure 2. The ultimate goal is to have an accurate and manageable computational capability. This is guided and validated by both fundamental and configuration specific experiments. A very important ingredient, one which links the other two and makes the solution understandable and manageable, is the modeling of the key fundamental physics. When all of this is worked together the potential for success is greatly enhanced.

This model doesn't just happen, however, just because we say it is a good model. It takes the coordinated effort of a committed team. The first ingredient to this is to get a wide range of talent and input. The Coolant Flow Management Team began the process with a tour of several of the aircraft engine manufacturers, presenting their preliminary thoughts and seeking guidance to formulating a strong and meaningful program. Earlier, Dr. Ray Gaugler of NASA Lewis surveyed the industry regarding the advisability and recommended thrust for a restart of film cooling at NASA. As a result of these visits, surveys and discussions, the team made a number of modifications to the origin plan. Industry expressed strong support for pursuing a computational film cooling capability, but cautioned that it couldn't be computationally overwhelming. They encouraged detailed studies of the internal passages for understanding and modeling, but not for design. They encouraged an effort to understand and couple the bleed from the internal passages to film cooling and how it affected the heat transfer on both sides. The industry partners did more than provide guidance. Several are performing research contracts or providing cooperative input.

As a result of all of this investigation and discussion the research planning team identified turbulence modeling, grid generation and validation data as the essential elements in the program.

Finally, the team looked to the university community for its expertise. Several research grants have been put into place, including three grants that were the result of an open solicitation for innovative university research in film cooling. The resulting government/industry/university partnership is illustrated in figure 3. A key to success of this partnership will be strong communication among all of the players, not just the government team. While this exists to some extent, it is an area that is still developing. The program is relatively new. However, there are other models at NASA, such as the By-Pass Transition Program and the Multi-Stage Flow Physics Program, that have successfully employed this model.

Another key feature of the strategy is planning. The research team needs to have a good understanding of the research objectives and has to come to some agreement as to the best use of the available resources to meet that objective. One approach is to use traditional TQ techniques, such as the fishbone charts, illustrated in figure 4. Using such instruments, the team established a corporate opinion as to the elements needed in the program to lead to a high expectation of success. Also, to know where to place emphasis, and how to evaluate progress. Of course, it is necessary to be sure that both people and money are assigned to these areas. Such charts exist, but they are considered a bit sensitive and are not included herein.

Finally, while it is not necessarily true of all research, an effort such as this has to have very specific goals and timelines to meet those goals. In consultation with industry, regarding timeliness, and after discussions within the team, regarding reasonable potential for success, a goal of having significant improvement in current capability by 1998 was established. This is shown in figure 5 and the Coolant Flow Management Team is working to that end.

## COOLANT FLOW MANAGEMENT

Before going into the details it is probably necessary to define what we mean by Coolant Flow Management. Using a typical, albeit somewhat old, high pressure turbine blade cooling flow configuration, figure 6, one can simply state that coolant flow management is the technical capability to make design decisions on the amount and location of cooling air flow, both on the inside and the outside of the blade to achieve maximum performance at minimum coolant air supply per blade. It is the goal of the Coolant Flow Management Program to develop new technical tools that will allow turbine heat transfer designers to assemble a design analysis system which they feel will substantially enhance their ability to do this. One will note that it is not a goal to provide a design method. This is outside of the expertise and responsibility of the team. The goal is to provide an integrated set of technical tools that allow the turbine heat transfer designer to do that.

The key features of the problem are illustrated in figure 7. Hot gas passes over the rotating blade. A film of air, taken from the later stages of the compressor, is injected close to the surface to form a protective blanket of coolant. The success of the injected coolant flow is dependent on many variables: the free-stream turbulence, the upstream wakes, the rotational forces and secondary flows, and the details of the flow out of the holes. Inside the blade the same is true, except for wakes. On the other hand a new complication is added in the form of ribs and other devices to enhance turbulence and increase heat transfer. One will note that the primary flow direction is radial, adding another complication, buoyancy and Coriolis forces. One will also note that the flow into the film coolant holes is most often at right angles to the main coolant flow direction. Finally, the sketch was deliberately drawn to show that optimum placement of holes on one side might not be optimum on the other. Thus coolant hole entrances could be in many positions relative to the protruding turbulence promoters.

It is this complex interaction between the inside and outside flow, as it enters and exits the holes, which is the focus of the research and certainly qualifies it as a title problem for a session on Heat Transfer in Complex Flows.

## INTERNAL CHANNEL SIDE OF THE PROBLEM

A fair amount of effort at NASA Lewis and elsewhere has already been directed to the internal coolant channel side of the problem. The research at NASA was motivated by an attempt to predict the flow and heat transfer in an advanced concept cooled radial turbine. The objective was supported by both an experimental and computational attack. Today, it serves as a good beginning to the current effort. To support research an experiment was conducted in what was known as the "Branched Duct" by Russell et. al. (1993, 1996). It attempted to capture the key features of the cooled radial turbine problem, albeit without rotation. The results of this experiment provide a highly detailed dataset and, although the configuration is no longer of primary interest, the dataset remains an excellent challenge to the task.

Accordingly, the computational community has been addressing this problem. The Coolant Flow Management team have also used this problem to test their approach. As they approached this problem the team, using the thinking illustrated in the fishbone charts of figure 4, agreed upon a grid and algorithm approach to the problem. The team agreed that an emphasis on doing the best in

each technical area would not necessarily produce the best integrated result, Thus, the team selected a multiblock grid approach as their choice between advanced technology and proven capability. They selected the commercial grid code GRIDPRO (1993) as meeting this need. An example of the results, beginning with the grid are shown in figure 8. The figure also illustrates the key features of the branched duct experiment geometry. Intuitively one would anticipate that this was a good grid choice. It should be noted that, while the geometry is relatively simple, it comprehends most of the major features, except rotation. The key features are the flow split and the turbulence promoting pins. If the analysis can capture the flow split and the heat transfer behind the pins, it will be a significant step forward. The team have also settled on a 3D Navier-Stokes code, the TRAF3D code of Arnonne et. al. (1991), as the code they will use.

Computational results, produced by Steinthorsson, et. al. (1996) are shown in figure 9a. The results, compared with the experiment of Russell et. al. (1993, 1996) in figure 9b are promising. The key features are captured. One would not expect the Baldwin-Lomax model to resolve the area behind the pins. This is an area for more work

The team has now turned their attention to geometries that are more typical of cooled axial turbines, the serpentine passages with turbulence promoting ribs. These geometries have actually received a considerable of study both experimentally and analytically and the team intends to use those results. However, they are not aware of any approaches at this time which include the film cooling bleed from the coolant channels - the main focus of the integrated study.

As a first step towards that objective, the NASA CFD team are developing their multiblock grid routines for such geometries and testing the results against experiments of Arts, et. al. (1992). Figure 10 shows a conventional single grid and a multiblock grid, as applied to the turn region of the Arts, et. al. duct. One can readily see how much nicer the multiblock grid wraps around the divider and goes into the square corners. The effect for the full channel is shown in figure 11. The research is being reported in a forthcoming paper by Rigby, et. al. (1996) They found among other things that the multiblock grid arrangement gave at least as good, if not better results, using only one third the grid points, figure 12. The results are compared to the Arts et. al. (1992) data in figure 13. The calculation appears to do a very good job in the upper corner and just around the divider. It appears to miss the re-attachment point and subsequent high heat transfer. The team are encouraged by these results and are pursuing methods to improve them, particularly looking at turbulence models. Under NASA grant Stephens, et. al. (1995a, 1995b) at Carnegie Mellon University are studying the details of the flow physics and heat transfer in the immediate region of the turbulence promoting ribs, also using a multiblock grid approach. The complexity of the flow field and heat transfer is shown in figure 14.

Lau, et. al. (1964) have been studying the serpentine passage geometry with turbulence ribs at NASA. The passage geometry is shown in figure 15 with liquid crystal results shown in figure 16. The geometry is currently being modified, as illustrated in figure 15 to include bleed out of the internal passages, as one would expect in a film cooled blade. The first experiments have the holes at 90 degree entrance angle. Other angles and orientations will be studied as the work progresses.

All of the above studies are at rather large scale and they are non-rotating. They are intended to help develop and validate the computational analyses. Their primary strength lies in the fact that a lot of detail can be studied and, as the developing research calls for it, changes are easy and inexpensive to make. However, the real turbine is rotating and very high buoyancy and Coriolis forces exist in the internal passages and must be addressed. Accordingly, part of the Coolant Flow Management program includes contracts at Pratt & Whitney/United Technologies Research Center (P&W/UTRC) (Wagner (1996)) and at Scientific Research Associates (SRA) (Tse (1996)). Both groups are using almost identical geometries, the very realistic one shown in figure 17. At P&W/UTRC the focus is on heat transfer, using the transient liquid crystal method for a heated model flowing air and rotating in a centrifuge. Although excellent heat transfer detail is evolving,

very little flow detail can be measured in this experiment. At SRA a companion rotating experiment is using a matched index of refraction technique and laser anemometry to get highly detailed maps of the flow field, such as illustrated for one section at one case in figure 18. At only four hydraulic diameters into the passage a counter-clockwise swirl and corner recirculation have already setup. Especially noteworthy is the asymmetry of the flow field. By its very nature the matched index of refraction technique requires an isothermal - no buoyancy force - flow field; however, it does include Coriolis forces and provides one more piece to the puzzle.

With all of these efforts the team feels that they truly have a comprehensive and well-integrated attack on the key heat transfer and fluid physics of the internal coolant channel with film cooling bleed.

## EXTERNAL FILM COOLING SIDE OF THE PROBLEM

A similar integrated attack is underway on external film cooling side with the same emphasis on understanding the details of the flow out of the hole and its effect on film cooling. The long term goal is to establish a computational film cooling analysis capability that is accurate and manageable, so that intelligent decisions can be made about the heat transfer design of cooled turbine blades.

One of the fundamental studies linking the inside to the outside is being conducted under NASA grant at the University of Minnesota by Simon (1996). The focus is on creating realistic, albeit non-rotating, entrance flow fields to the film cooling holes. A couple of these are illustrated in figure 19. The key features are twofold. First, the holes are very short, typically 2-3 L/D, as one would find in a turbine. The flow into the hole is at a variety of angles to the hole entrance and not necessarily on a streamline parallel to the hole center-line, again, as one might find in the internal passages of a turbine blade (c.f. figures 6 and 7). To begin the research Wang, et. al. (1996) studied the flow out of the holes with a fully developed (i.e. long) inlet. The results show that the transverse eddy diffusivity can be very high relative to the normal direction and these results will need to be incorporated into models for the film cooling hole injection region.

Another experiment is being conducted under NASA contract at Allison Engine Co. by Ames (1995). Using a cascade of airfoils, Ames is measuring both heat transfer and details of the turbulent flow field for flow both with and without film cooling. The results, figure 21, are showing that near the holes on the pressure surface, when the flow is subject to high freestream turbulence, the heat transfer with film cooling could actually be higher than without film cooling. This could be happening because a flow that would be otherwise laminar on the pressure surface is being disturbed by the coolant flow. It raises a question concerning the use of film cooling on the pressure side. Another unusual result is that the adiabatic effectiveness may actually be better near the hole when the free stream turbulence is higher, as shown in figure 22. Over most of the flow the trend is what one would anticipate, the free stream turbulence reduces effectiveness of the film coolant. The near hole effect might be explained by the turbulence spreading the coolant out faster. The CFD analyses should be able to explain these effects, if the analysis is to be successful.

The analysis that is currently underway and is the cornerstone for much of the work is that of Garg et. al. (1995a, 1995b, 1996), illustrated in figures 23 and 24. The analysis is a full Navier-Stokes analysis with several types of turbulence models available. At present the film cooling holes typically employ approximately 21 grid points. A variety of flow profiles out of the holes have been studied. The code is quite well developed and early comparisons with data have been promising and have provided considerable help in guiding the overall program. One of the long term goals of the program is to provide computational tools that will accurately and efficiently allow one to explore the effect of changes in geometry on film cooling effectiveness, such as illustrated in figure 24, showing different injection patterns for the showerhead holes. At present these calculations use about 1-2 million grid points, requiring the memory of the Cray-90, and take about 12 hours on the Cray-90 for the initial case (5 hours for follow-up cases, such as in figure 24).

Furthermore, while early comparisons are promising, their accuracy as yet to be fully established. This why so much attention is being paid to the hole region. So we can accurately model the flow and use these models to speed the calculation and assure the accuracy.

Accordingly, in addition to the studies at the University of Minnesota, there is a study at Ohio State University under a NASA Graduate Student Research Fellowship (GSRP) to study internal coolant plenums and their effect on film cooling effectiveness. There is a grant at Louisiana State University to develop an LES database on the flow physics around the hole, and another NASA GSRP at University of Arizona by Quintana, et. al. (1996) to study film cooling augmentation by active flow control.

To support this code and model development a transient liquid crystal film cooling cascade is under construction at NASA Lewis. It is a vane configuration and the recommended design for it was supplied by Dr. David Winstanley of Allied Signal. A stereolithography model of the vane, supplied by Allied Signal, is shown in figure 25. The experimental research team conducting both this experiment and the internal coolant with bleed experiment will be working closely with the modelers and the code developers, as well as the other experimentalists, to get the most out of these experiments, focusing on the full integration.

Finally, just as on the coolant channel side, the film cooling flow is really subject to rotation. However, on the external side it is the effect of wakes on the film cooling, rather than buoyancy and Coriolis forces, which is probably the biggest concern. Will the wakes seriously disturb the film cooling flow? A computational and analytical study is underway a NASA Lewis by Heidmann et. al. (1996) to study wake effects. The experiment is being conducted in an annular cascade with a spoked wheel disturbance generator, as shown is figure 26. The analysis is well underway and one frame from the time-resolved calculation is shown in figure 27. The computational results are showing a rather sharp fluctuation in the heat transfer in the stagnation region near the film cooling hole rows. The results are expected early this year. A companion experiment is also well underway at Texas A&M University by Hui, et. al. (1996). The Texas A&M experiment is using liquid crystal techniques in a low speed linear cascade with an upstream disturbance generator. The first tests without film injection are showing, as expected, higher heat transfer in the wakes. The work is continuing with film cooling injection. Rotor/stator interaction calculations on two different turbine stage configurations are also underway at Western Michigan University by Dorney (1993, 1995). These will form a baseline for future rotor/stator interaction calculations, which emphasize the effects on film cooling.

## CLOSING REMARKS

The Coolant Flow Management Program is off to a good start in putting in place the necessary ingredients for successfully attacking this very complex heat transfer process and arriving at a result, which will enhance our capability to build better performing, more thermally efficient turbines.

Once the models are developed to expedite analyses, an integration and optimization strategy can be put in place.

The success, however, will be highly dependent on the ability of all the players to continue to keep their research focused on the common goal. Good communication will be critical. Regular assessment of progress is important. In any endeavor, as complex as this, some of the initial ideas won't be the right ones. A steady and constructively critical sharing of progress and ideas will be most important. To this end the research team is making plans for the first Coolant Flow Management Workshop, composed primarily of the key contributors to the program, to be held sometime in 1996.



The complex heat transfer problems need strategies for success. The Coolant Flow Management Program is one such strategy. Hopefully, it can be a model. Certainly others are possible; however, I would contend that these problems cannot be solved in isolation.

## REFERENCES

- Ames, F. (1995) Private communication via monthly progress reports.
- Arnonne, A., Liou, M.-S., and Povinelli, L. A. (1991) "Multigrid Calculation of Three Dimensional Viscous Cascade Flows," AIAA Paper AIAA-91-3238.
- Arts, T., Lambert, de R., Rau, M. and Acton, P. (1992) "Aero-Thermal Investigation of the Flow Developing in a 180 Degree Turn Channel." VKI-Preprint No. 1992-10.
- Dorney, D. J., and Davis, R. L. (1993) "Numerical Simulation of Turbine 'Hot Spot' Alleviation Using Film Cooling," AIAA Journal of Propulsion and Power, Vol. 9, No. 3, May-June 1993, pp. 329-336.
- Dorney, D. (1995) Private communication via monthly progress reports.
- Garg, V. K. (1996) "Adiabatic Effectiveness and Heat Transfer Coefficients on a Film-Cooled Rotating Blade," Paper to be presented at the 41st ASME International Gas Turbine and Aeroengine Congress and Exposition, Birmingham, UK, June 1996.
- Garg, V. K. and Gaugler, R. E. (1995a) "Effect of Velocity and Temperature Distribution at the Hole Exit on Film-Cooling of Turbine Blades," ASME Paper 95-GT-2, accepted for publication in the Journal of Turbomachinery.
- Garg, V. K. and Gaugler, R. E. (1995b) "Leading Edge Film Cooling Effects on Turbine Blade Heat Transfer," ASME Paper 95-GT-275, accepted for publication in Numerical Heat Transfer.
- Heidmann, J. (1995) "Numerical Study of the Effect of Wake Passing on Turbine Blade Film Cooling," AIAA Paper AIAA 95-3044
- Iacovides, H. and Launder, B. E. (1995) REVIEW "Computational Fluid Dynamics Applied to Internal Gas-Turbine Blade Cooling - a Review," International Journal of Heat and Fluid Flow, Vol.16, No. 6, pp.454-470, December 1995.
- "GRIDPRO (TM) /az3000, Users Guide and Reference Manual", (1993) Program Development Corporation, White Plains, NY.
- Lau, S. C., Russell, L. M., Thurman, D. R., and Hippensteele, S. A. (1994) "Visualization of Local Heat Transfer in Serpentine Channels with Liquid Crystals," Paper presented at the 5th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery, Kaanapali, Maui, HA, May 1994.
- Quintana, D., Amitay, M., Likhachev, O., Ortega, A., and Wagnanski, I. (1996) "Augmentation of Film Cooling Heat Transfer by Active Flow Control," Paper presented at the Engineering Foundation TURBULENT HEAT TRANSFER Conference, San Diego, CA March, 1996.

- Rigby, D. L., Ameri, A. A., and Steinthorsson, E. (1996) "Internal Passage Heat Transfer Prediction Using Multiblock Grids and a k-e Turulence Model," paper submitted for the 1996 41st ASME International Gas Turbine and Aeroengine Congress and Exposition.
- Russell, L. M., Hippensteele, S. A., Poinsatte, P. E., Thurman, D. R., and Simonyi, P. S., (1993) "Measurement and Computational Analysis of Heat Transfer and Flow in a Simulated Turbine Blade Internal Cooling Passage," AIAA Paper AIAA-93-1797.
- Russell, L. M., Thurman, D. R., Hippensteele, S. A., and Poinsatte, P. E. (1996) "Measurement of Heat Transfer, Flow, and Pressures in a Simulated Turbine Blade Internal Cooling Passage," NASA TP in progress.
- Simon, T. W., (1996) Private communication
- Simoneau, R. J. and Simon, F. F. (1993) REVIEW, "Progress Towards Understanding and Predicting Heat Transfer in the Turbine Gas Path," International Journal of Heat and Fluid Flow, Vol. 14, No. 2, pp. 106-128, June 1993.
- Steinthorsson, E., Ameri, A. A., and Rigby, D. L. (1996) "Simulation of Turbine Cooling Flows Using Multiblock-Multigrid Scheme," AIAA Paper AIAA 96-0621, 34th Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 1996.
- Stephens, M. A., Shih, T. I-P., and Civinskas, K. C. (1995a) "Computation of Flow and Heat Transfer in a Rectangular Channel with Ribs," AIAA Paper AIAA 95-0180, 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 1995.
- Stephens, M. A., Rimlinger, M. J., Shih, T. I-P., and Civinskas, K. C. (1995b) "Chimera Grids in Computing Flowfields in Turbine-Blade-Internal-Coolant Passages," Journal of Propulsion and Power, Vol. 11, No. 2, pp. 213-220, March-April 1995
- Tse, D. G. N. (1996) "Flow in Rotating Serpentine Coolant Passages with Skewed Trip Strips," SRA Final Contract Report R95-9089F, NASA CR in progress.
- Wagner, J. (1996) Private communication via monthly progress reports.
- Wang, L., Tsang, H., Simon, T. W., and Eckert, E. R. G. (1996) "Measurements of Mean Flow and Eddy Transport over a Film Cooled Surface," paper submitted to the 1996 National Heat transfer Conference, Houston, TX, August 1996.

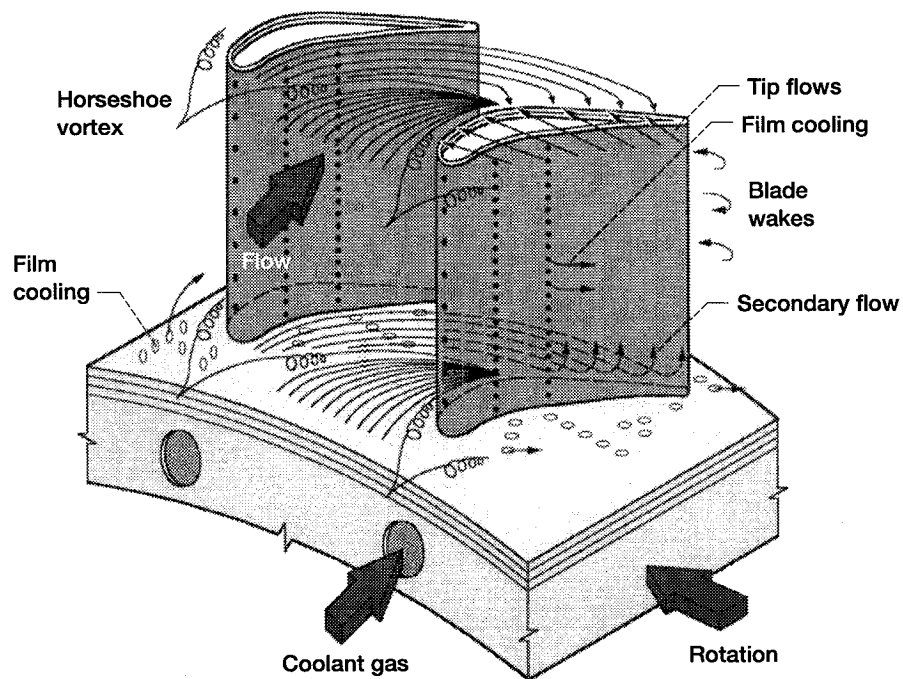


Figure 1.—Complex heat transfer phenomena in the turbine gas path.

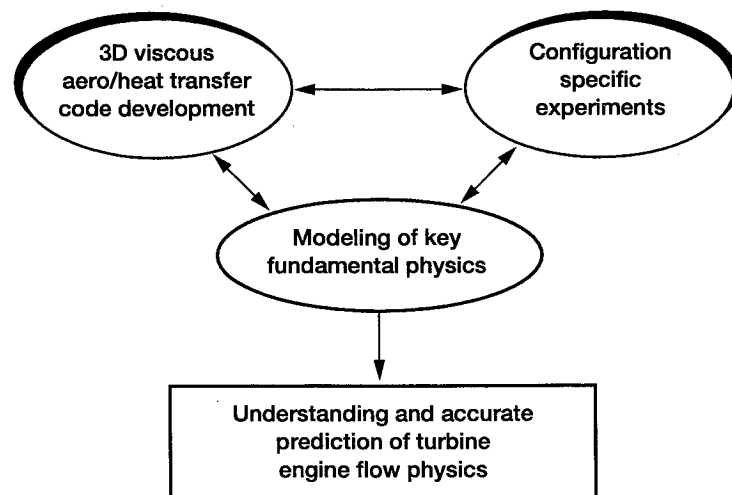


Figure 2.—Research model.

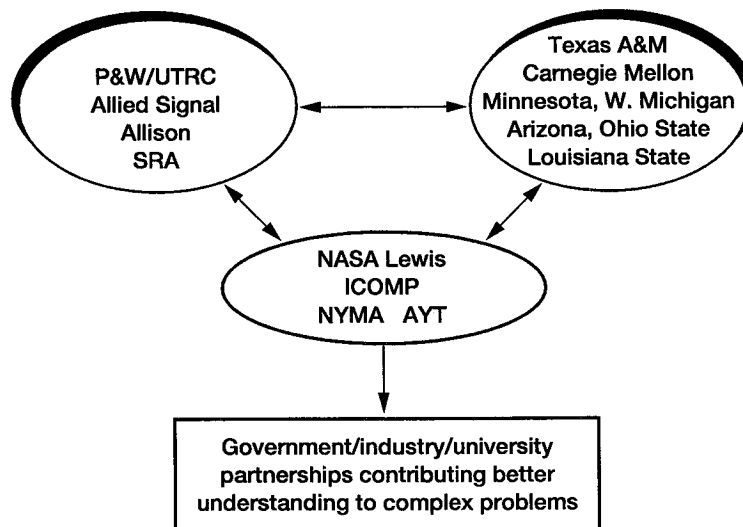


Figure 3.—Partnership model.

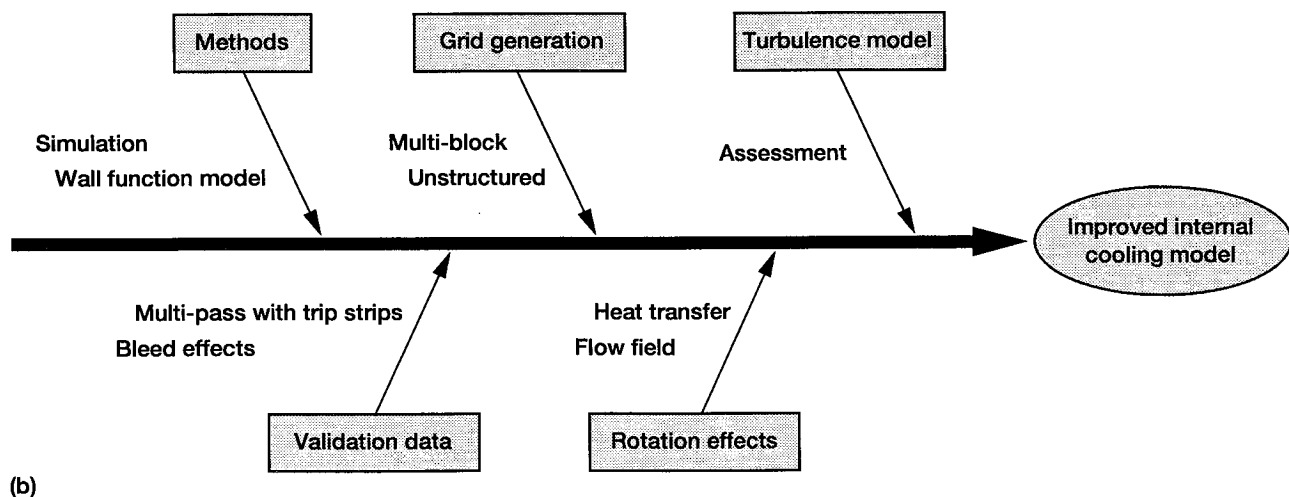
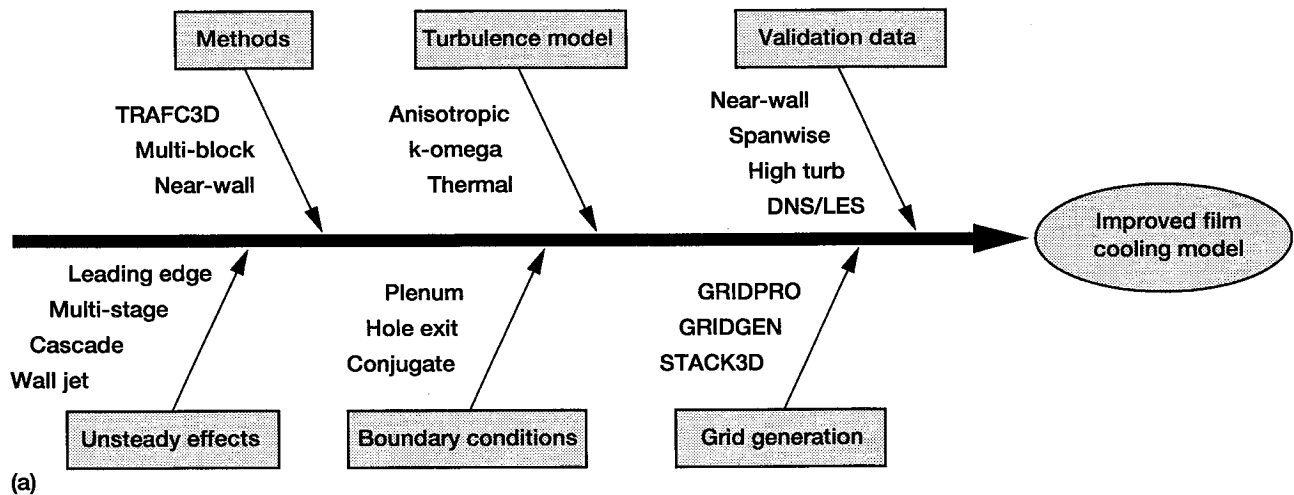


Figure 4.—Application of TQ principles to research strategy. (a) Fishbone diagram of the film cooling elements. (b) Fishbone diagram of the internal cooling elements.

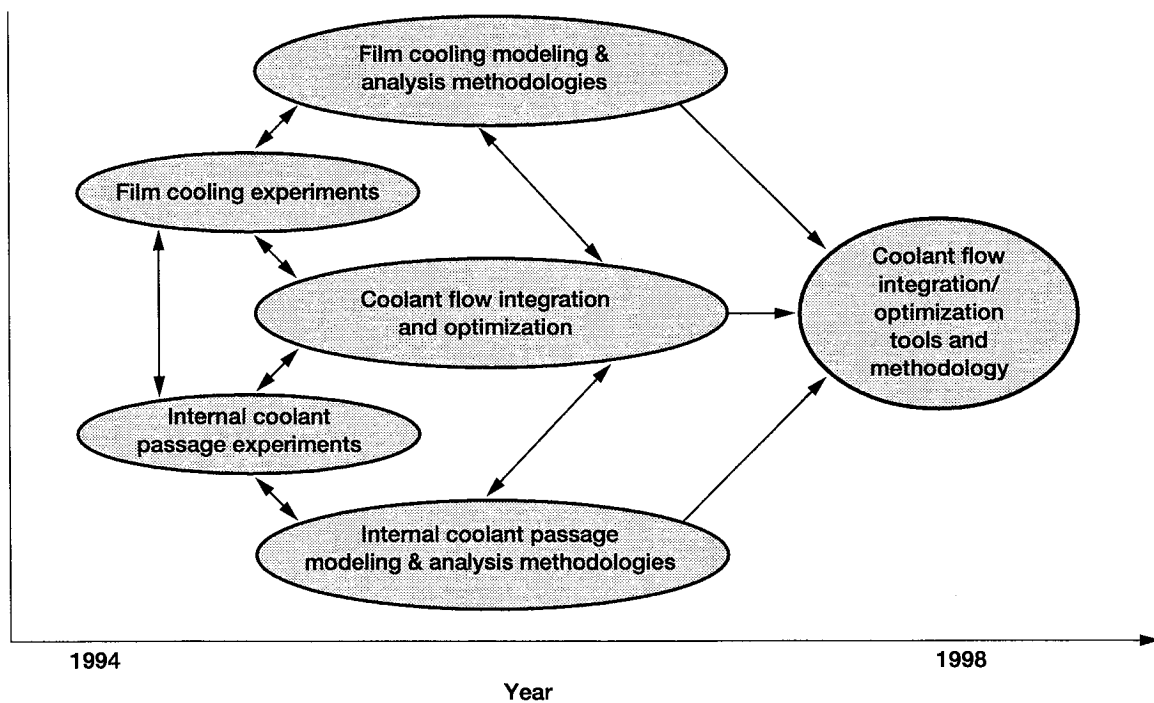


Figure 5.—Research interactions and timeline for the coolant flow management program.

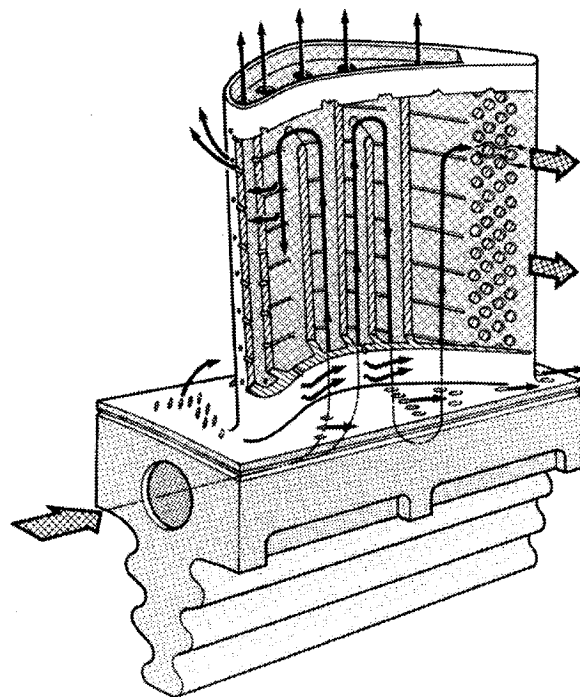


Figure 6.—Typical cooled turbine blade configuration, illustrating the complex interactions between the internal and external flow.

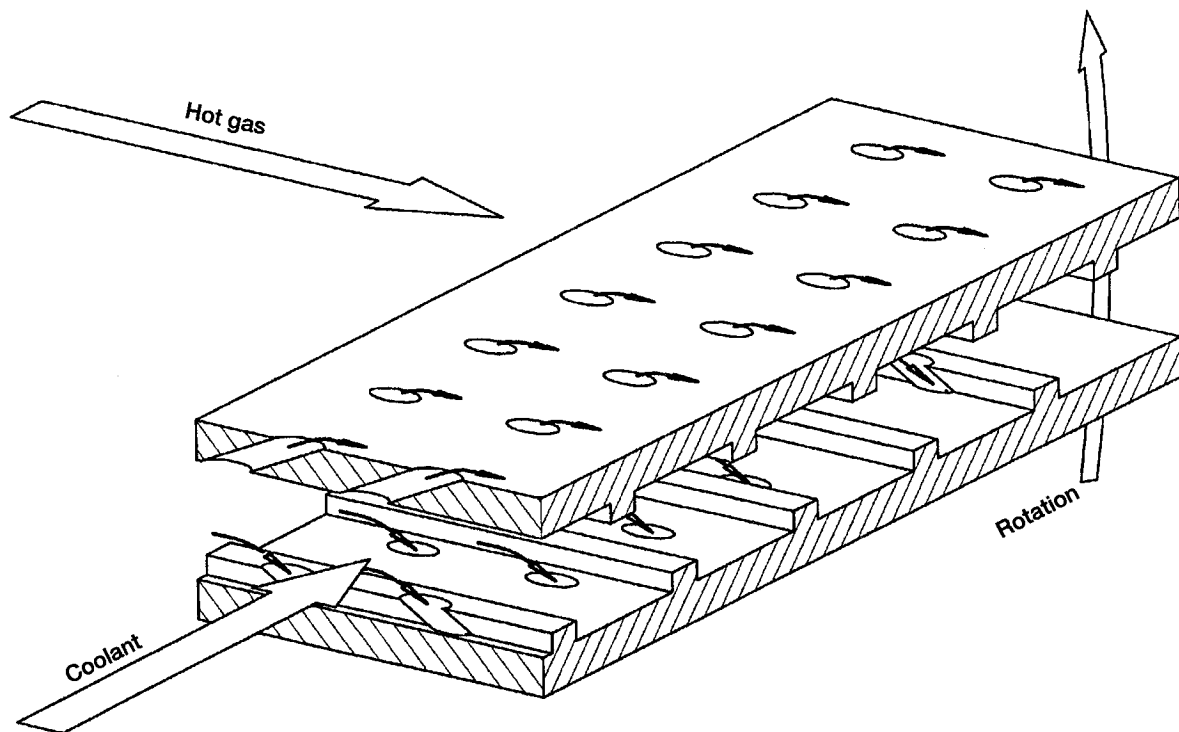


Figure 7.—Idealized slice of a cooled turbine blade.

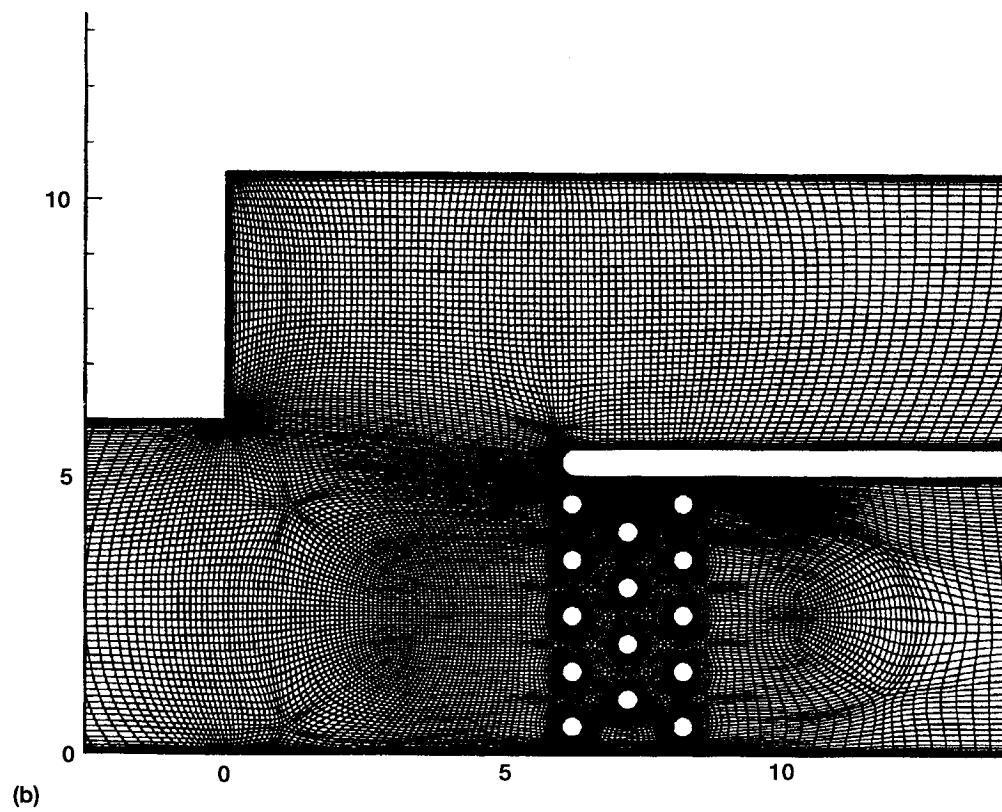
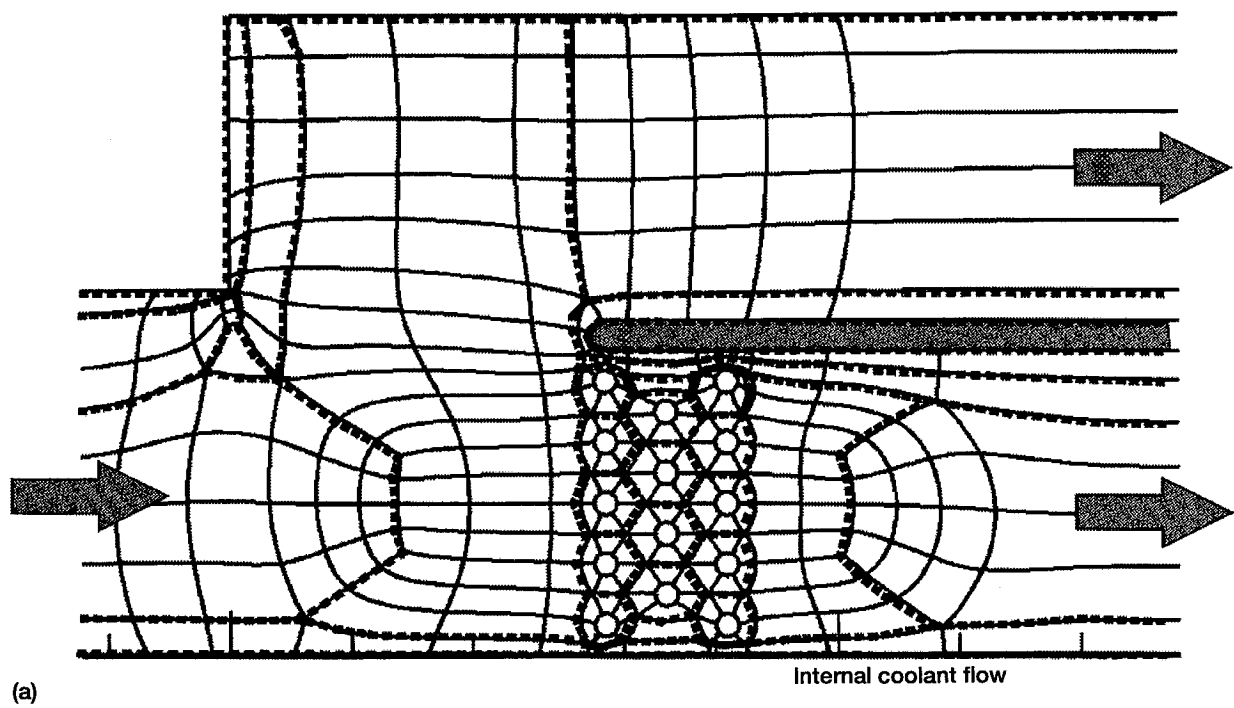


Figure 8.—Use of GRIDPRO Multiblock code for the analysis of the branched duct experiment. (a) 283 block topology reduced to 27 blocks. (b) Full grid.

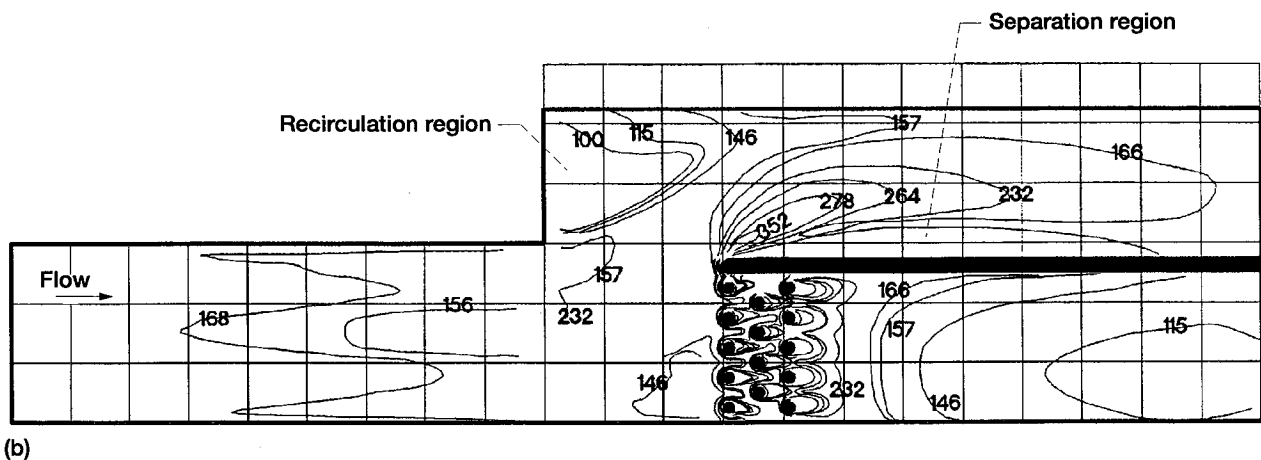
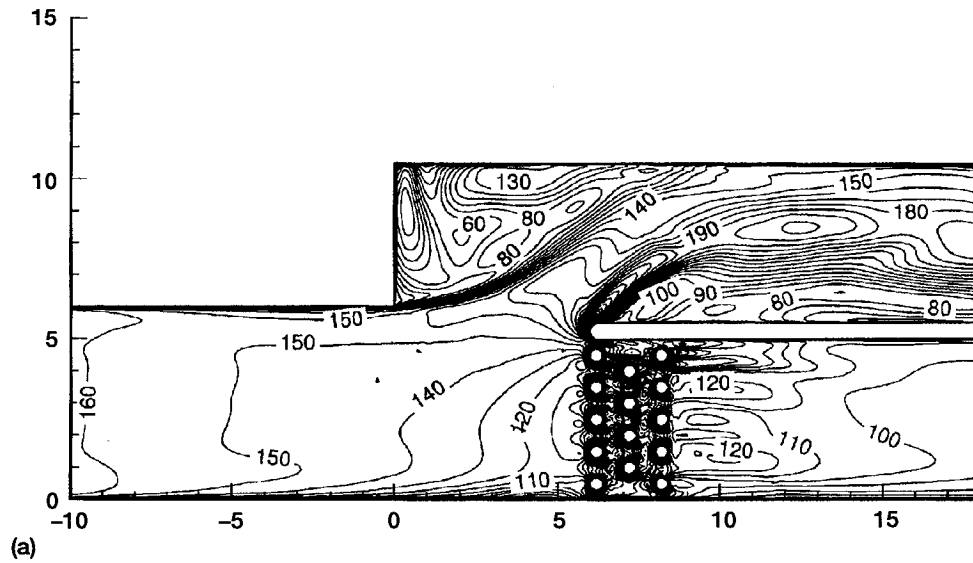


Figure 9.—Heat transfer in the branched duct ( $Re = 335,000$ ). (a) Analysis, using Baldwin-Lomax turbulence model. (b) Experimental heat transfer coefficients ( $W/m^2/K$ ).



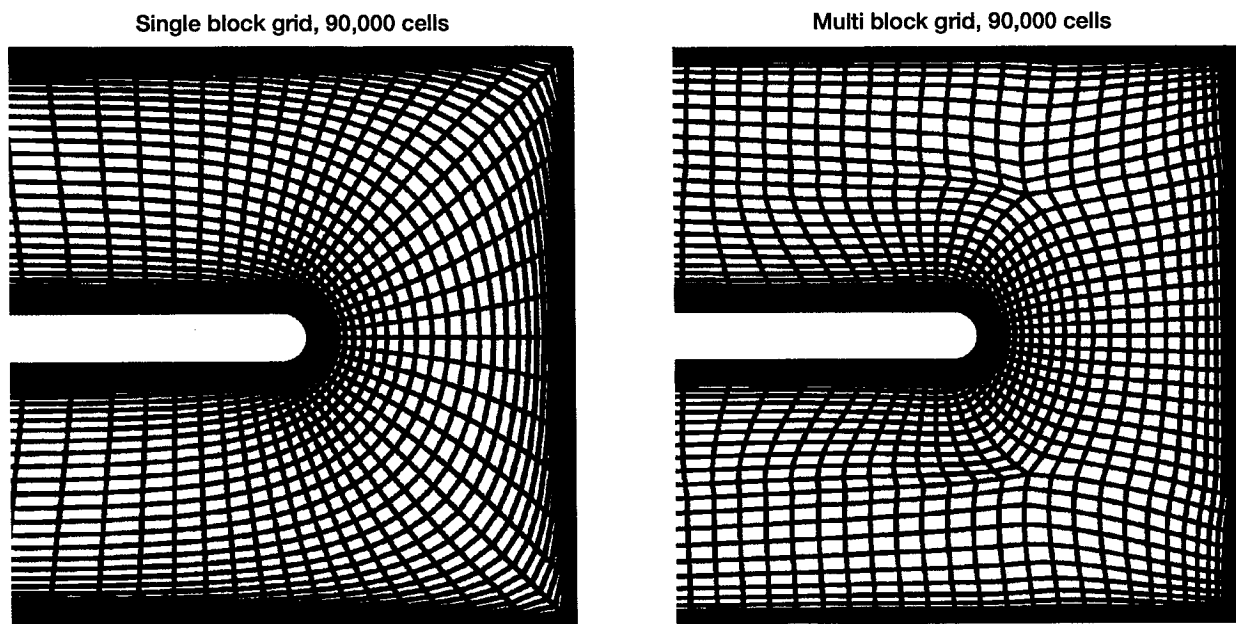


Figure 10.—Expanded view of turn region in 180 degree turn duct, comparing single and multiblock grids.

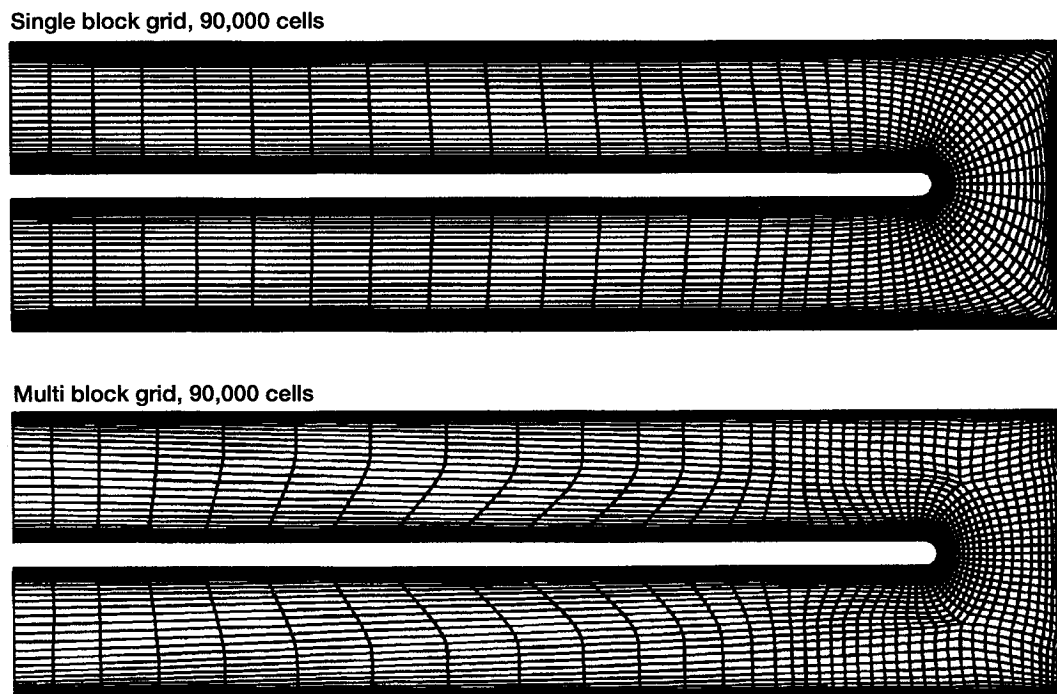


Figure 11.—Full view of the 180 degree turn duct, comparing single and multiblock grids.

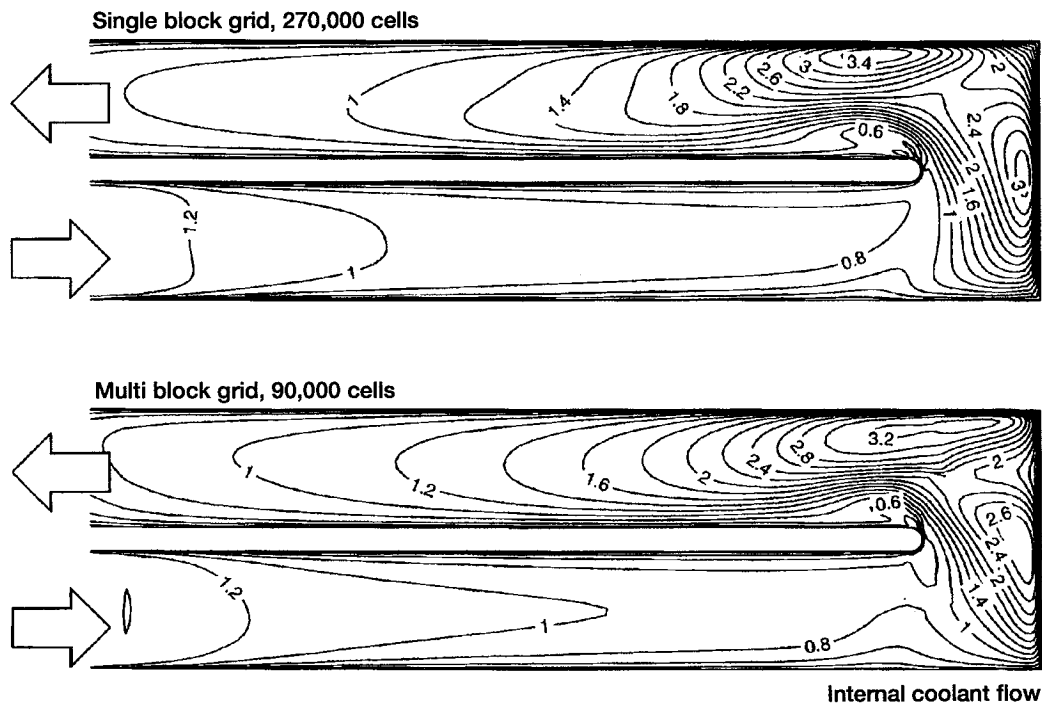
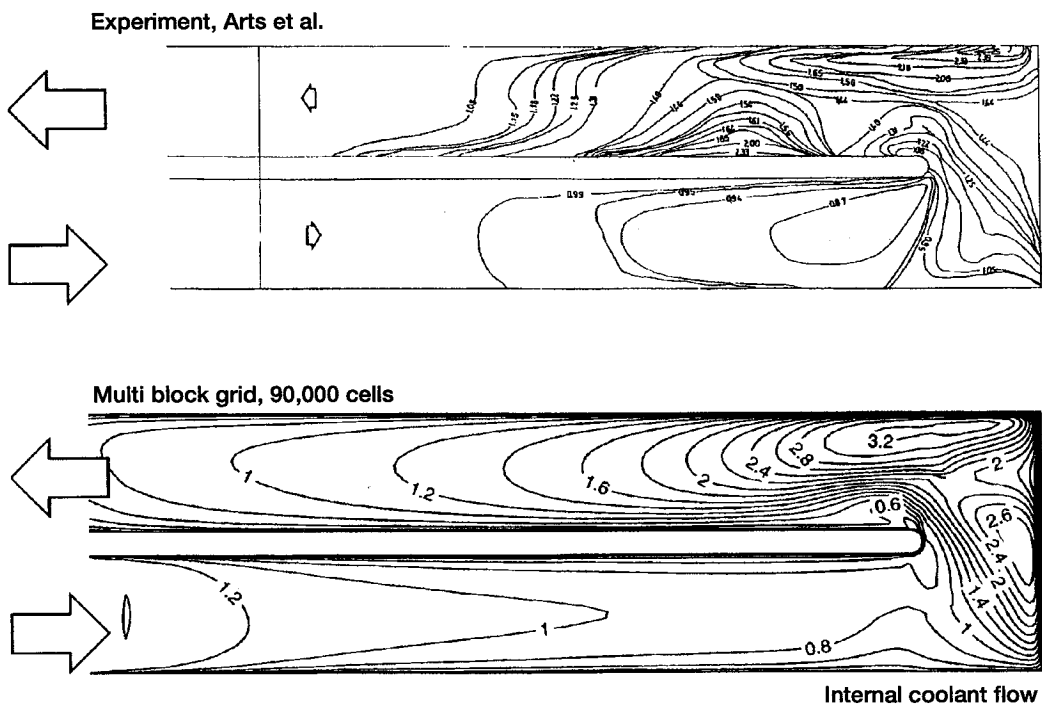


Figure 12.—Normalized Nusselt number on lower surface of the 180° turn duct, using single and multiblock grids ( $Re = 18,000$ , aspect ratio = 0.5, fully developed inlet).



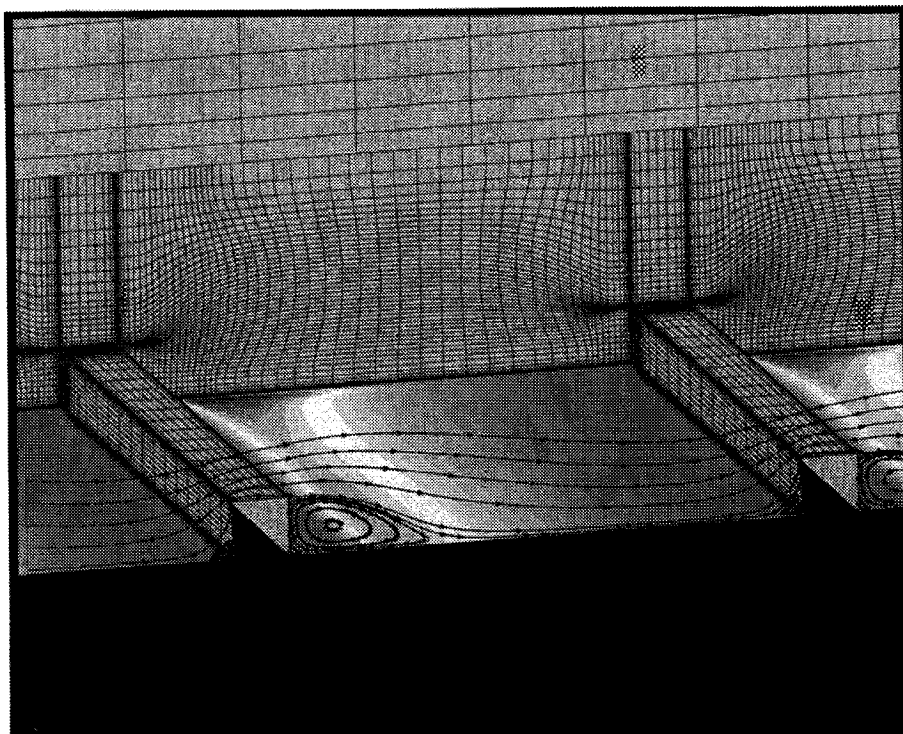


Figure 14.—Application of multiblock grid techniques to a detailed study of the heat transfer and flow in the rib region of an internal channel.

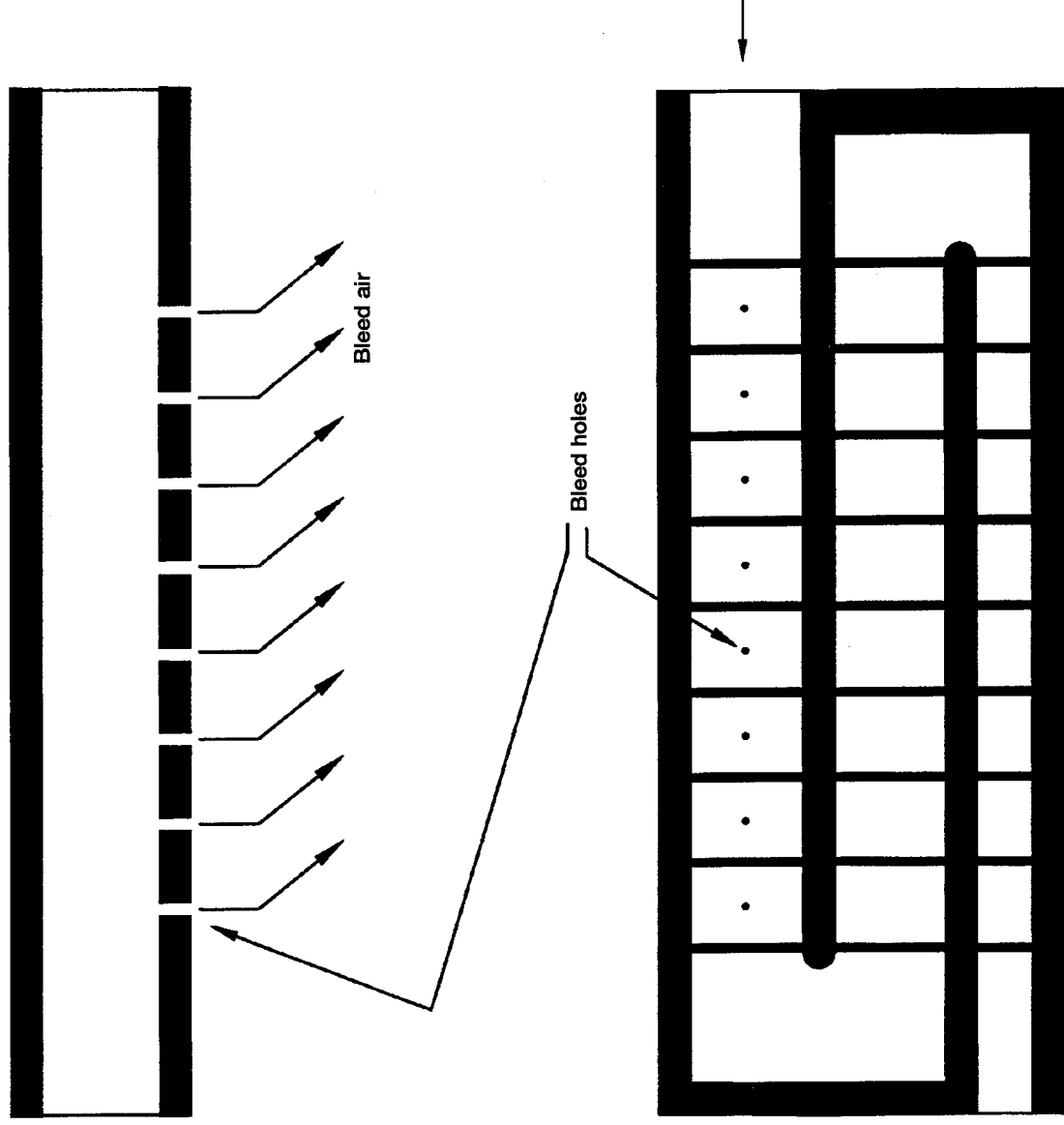


Figure 15.—Internal cooling channel with bleed air.

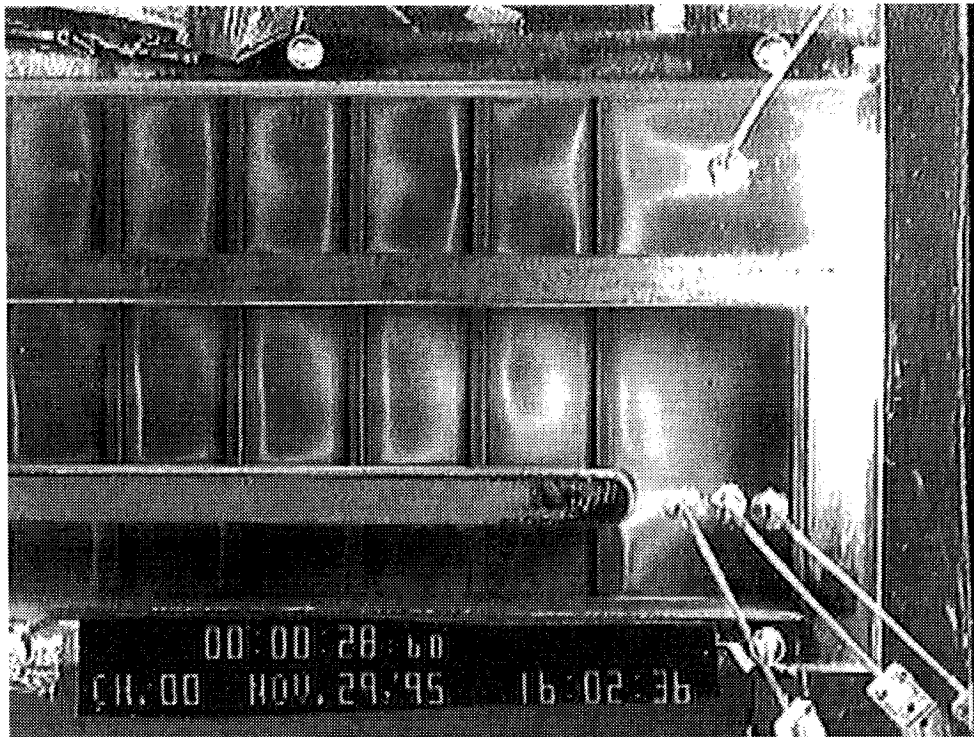


Figure 16.—Liquid crystal heat transfer patterns for internal cooling channel with ribs, but without bleed.

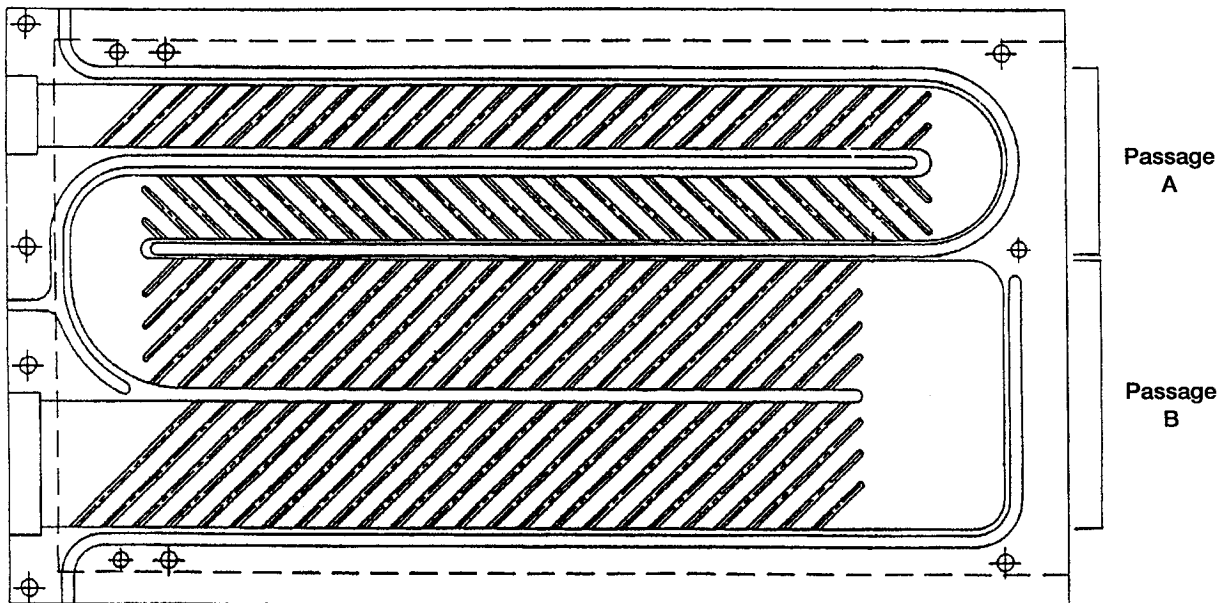


Figure 17.—Model of turbine blade cooling passage with ribbed walls being used in both heat transfer and flow experiments with rotation.

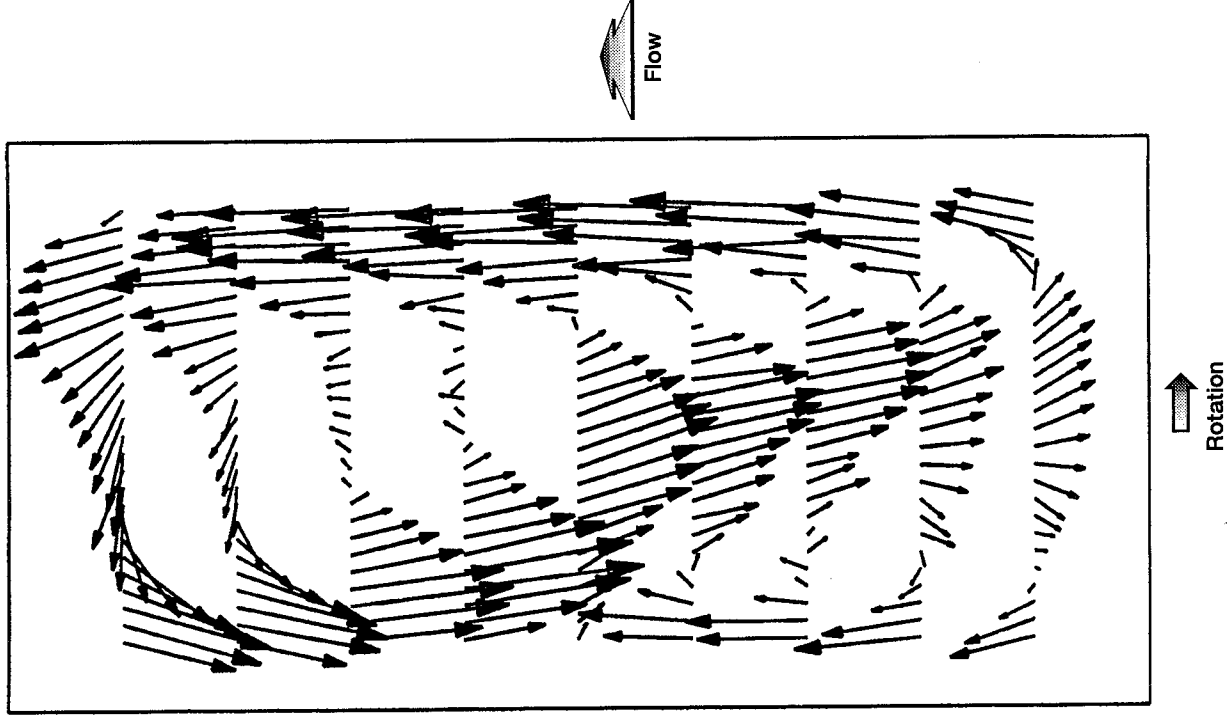


Figure 18.—Tangential velocity vectors in the first outward flowing leg at 4 diameters in the 2:1 channel.

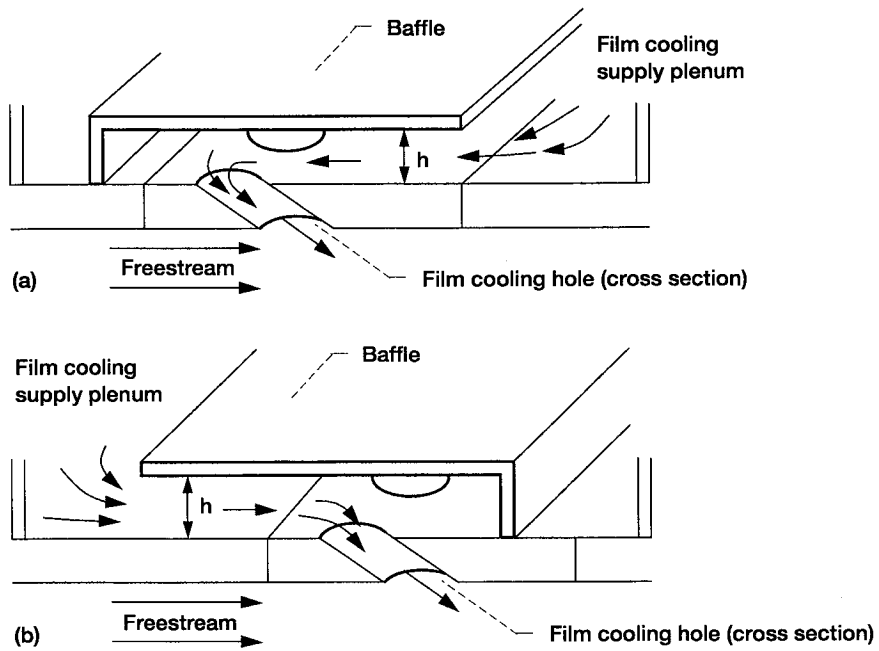


Figure 19.—Sketch of experiment to study bleed region flow effect on film coolant flow. (a) Counter-to-freestream. (b) Parallel-to-freestream.

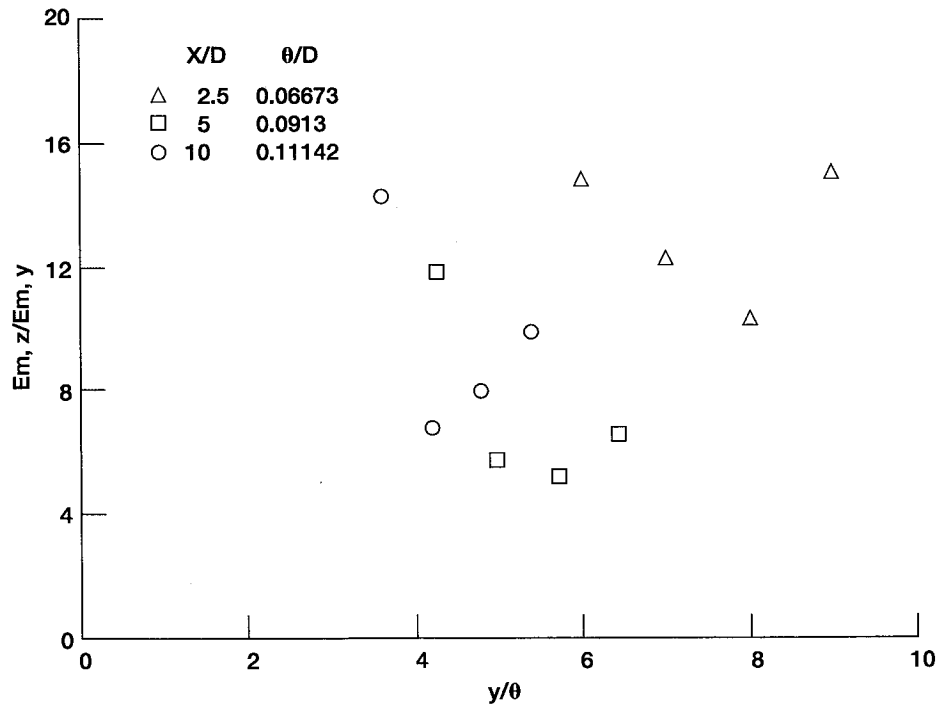


Figure 20.—Eddy diffusivity ratio in the region near a film cooling hole with a fully developed inlet.

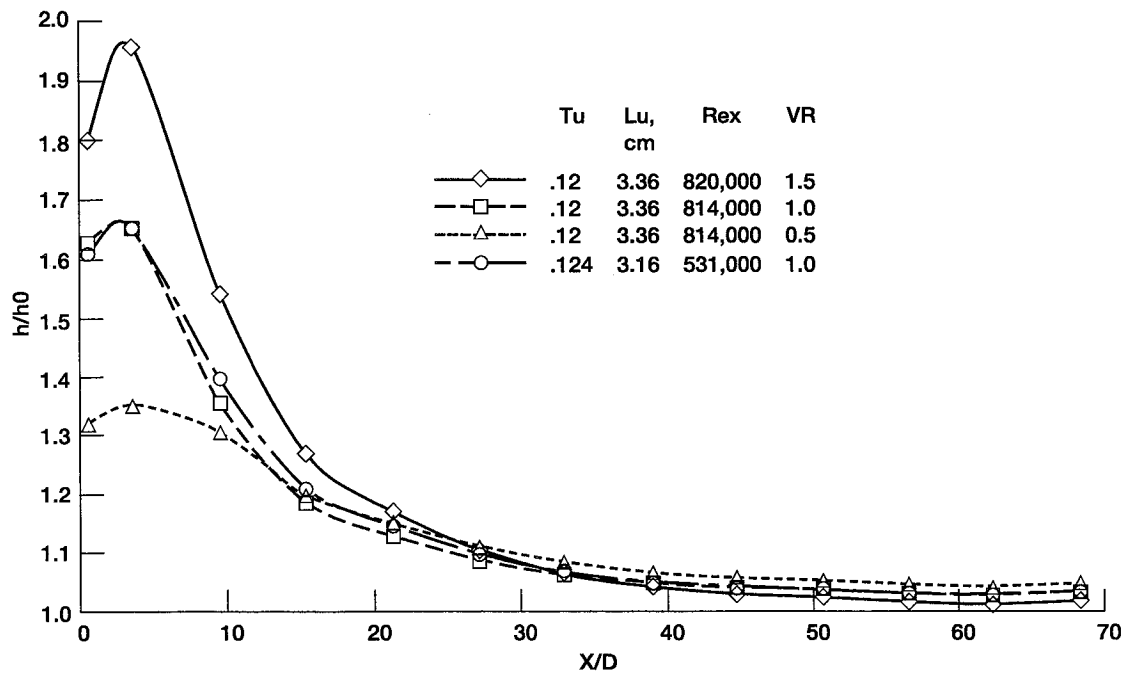


Figure 21.—Pressure surface blown over unblown heat transfer ratio (local values) for a range of velocity ratios with high turbulence, 2 rows, 30°, S/D = 3.

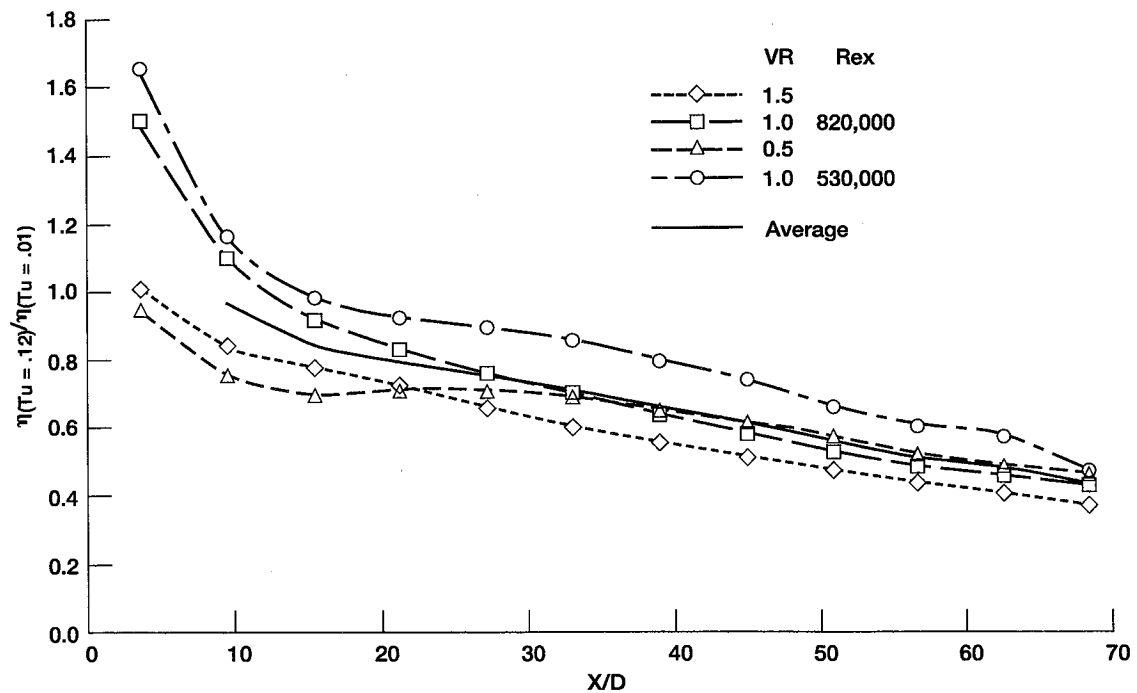


Figure 22.—Influence of turbulence on relative level of pressure surface adiabatic effectiveness, 2 rows, 30°, S/D = 3.



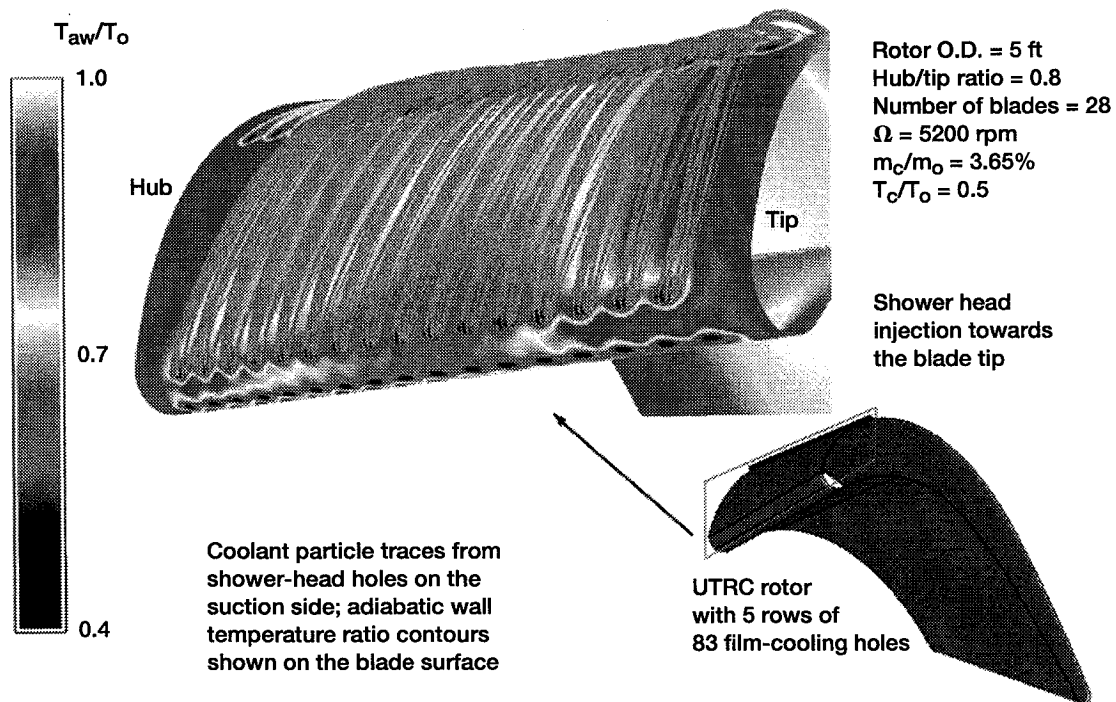


Figure 23.—Computational film cooling.

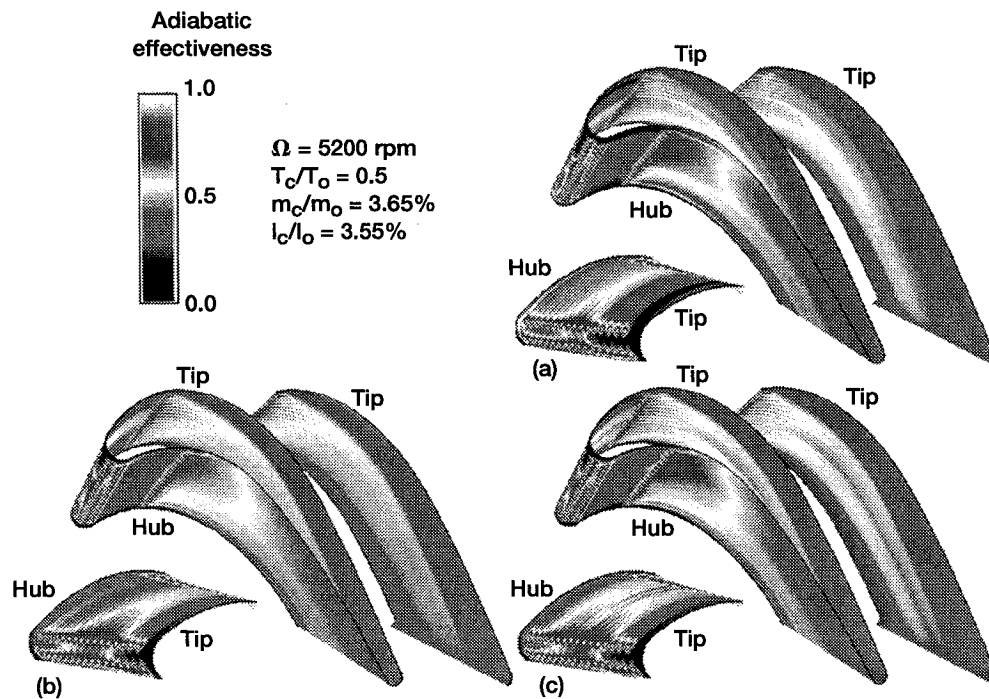


Figure 24.—Use of CFD to study the effect of coolant injection pattern on film cooling effectiveness — UTRC rotor. (a) All shower-head holes inject towards the hub. (b) All shower-head holes inject towards the tip. (c) All shower-head holes inject towards tip except 8 near hub on suction side that inject towards hub.

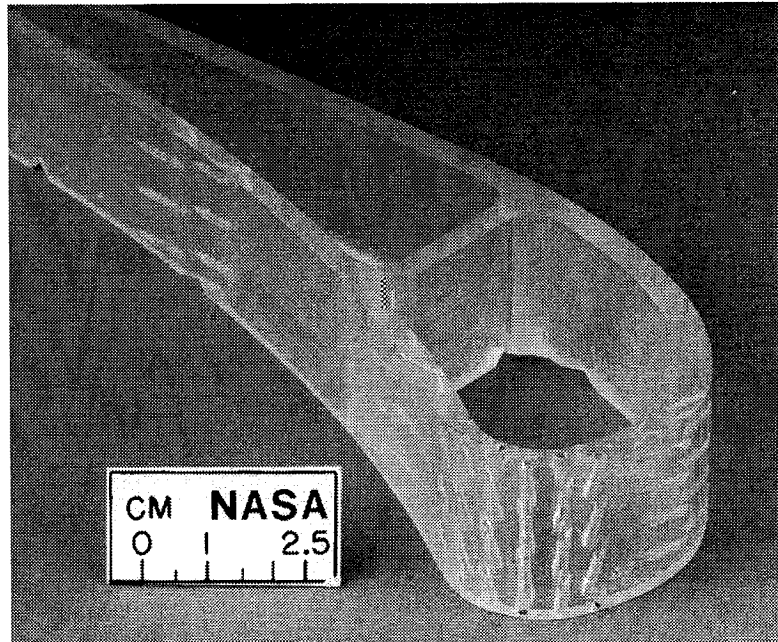


Figure 25.—Stereolithography model of a modern vane profile to be used in new film cooling heat transfer cascade.

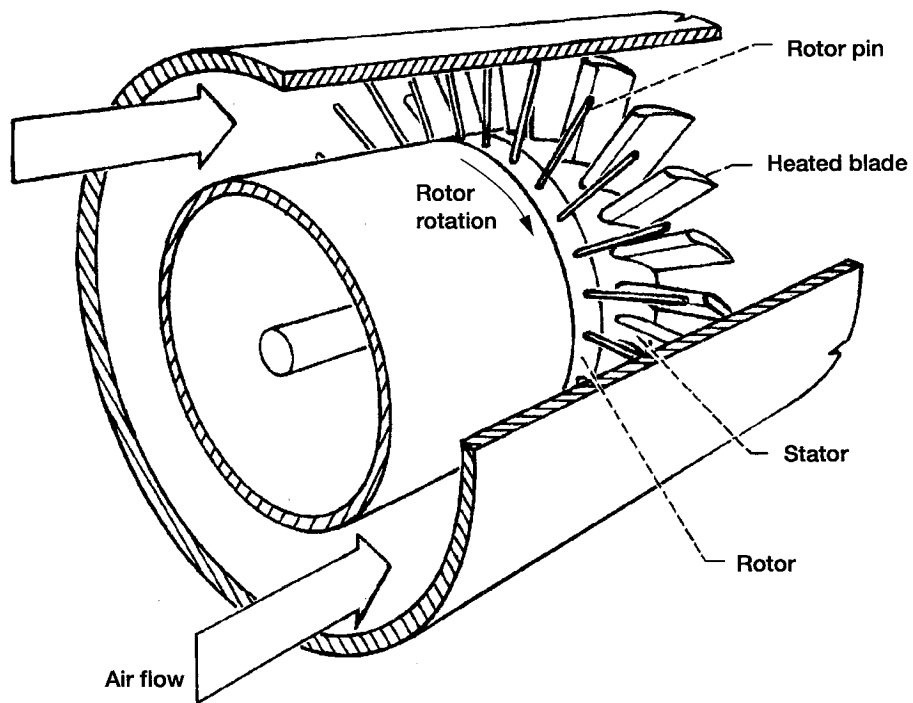


Figure 26.—Rotor-wake heat transfer rig.

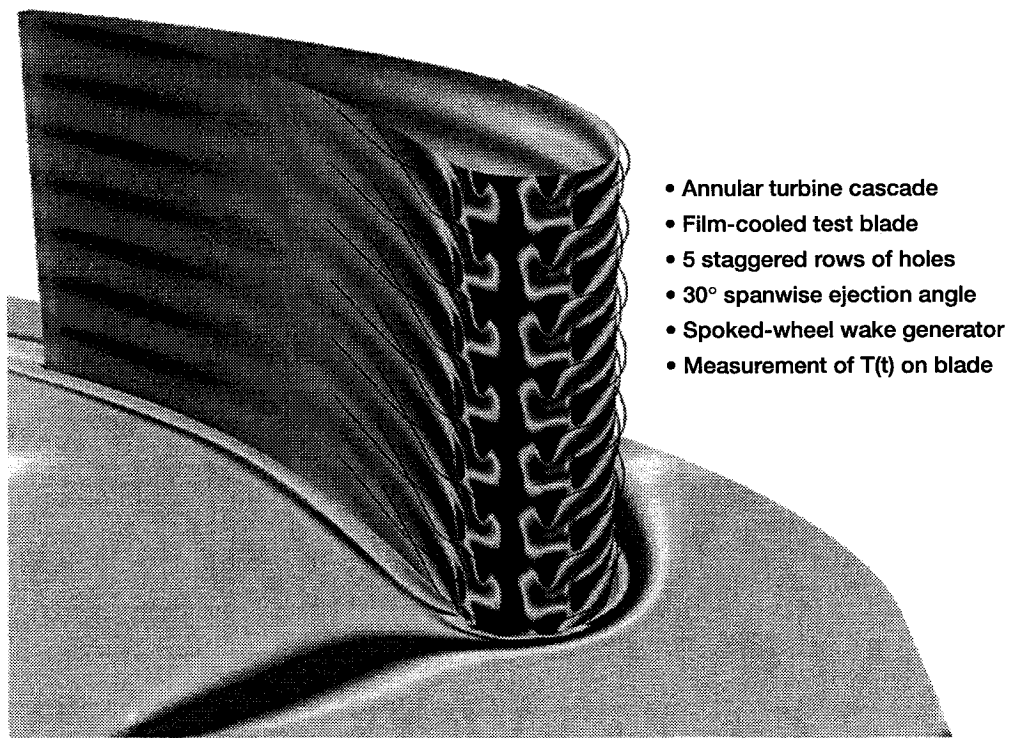


Figure 27.—Time-resolved effect of wake passing on turbine film cooling.

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13. ABSTRACT (Maximum 200 words)  There is no shortage of complex heat transfer problems, so the title problem is merely one with which the author is familiar and one for which we have a nice story to tell. Being more specific, the subject of this paper is a NASA research program, known as the Coolant Flow Management Program, which focuses on the interaction between the internal coolant channel and the external film cooling of a turbine blade and/or vane in an aircraft gas turbine engine. The turbine gas path is really a very complex flow field. The combination of strong pressure gradients, abrupt geometry changes and intersecting surfaces, viscous forces, rotation, and unsteady blade/vane interactions all combine to offer a formidable challenge. To this, in the high pressure turbine, we add the necessity of film cooling. The ultimate goal of the turbine designer is to maintain or increase the high level of turbine performance and at the same time reduce the amount of coolant flow needed to achieve this end. Simply stated, coolant flow is a penalty on the cycle and reduces engine thermal efficiency. Accordingly, understanding the flow field and heat transfer associated with the coolant flow is a priority goal. It is important to understand both the film cooling and the internal coolant flow, particularly their interaction. Thus, the motivation for the Coolant Flow Management Program. The paper will begin with a brief discussion of the management and research strategy, will then proceed to discuss the current attack from the internal coolant side, and will conclude by looking at the film cooling effort - at all times keeping sight of the primary goal the interaction between the two. One of the themes of this paper is that complex heat transfer problems of this nature cannot be attacked by single researchers or even groups of researchers, each working alone. It truly needs the combined efforts of a well-coordinated team to make an impact. It is important to note that this is a government/industry/university team effort.				
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